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FINAL SUMMARY REPORT

for

A DEAD WEIGHT PRESSURE BALANCE WITH EXTENDED RANGE TO 5000 PSIG

for

NASA Contract NAS8-5232
CSC Register Number 3-0726

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1. SCOPE

This engineering report, which constitutes a part of the scope of work defined by National Aeronautics and Space Administration Contract No. NAS8-5232, is intended to satisfy the requirements of the second paragraph of Article III of the Contract. The report covers the modification of a Dead Weight Pressure Balance (Schuler Balance), to achieve an extended range of 5,000 PSIG, system test results, and a general discussion of the system test results and performance.

2. SYSTEM CONFIGURATION AND OPERATION (1,200 PSI UNIT)

2.1 GENERAL

The extended range dead weight pressure balance utilizes the basic principle of the 1,200 PSI "Schuler Balance" with the exception of two modifications: namely, the addition of a back-pressure regulator and a three-way valve. Consequently, the "Schuler Balance" configuration and operation will be briefly outlined prior to discussion of the extended pressure range unit to facilitate a comparison of the similarities and differences existing between the two units.

2.2 SYSTEM CONFIGURATION

The Balance (No. 426745) furnished by the Contracting Agency utilized a system configuration shown by Figure 1. The basic Balance configuration is essentially a large version of a pharmaceutical balance. The fulcrums used are knife edges bearing against the bottom of a V-groove. A weight platform, capable of supporting an external weight or mass, is attached to the beam on one side of the main fulcrum. A rotating piston is located on the end of the beam opposite to that of the weight platform. One end of the piston bears against the beam and the other end is vented into a small cavity or pressure dome. Thus, two forces, such as an external weight placed on the platform or a pressure applied to the dome of the piston are capable of being reacted through the beam. With the beam in balance, the two applied moments are equal. If the two moment arms are equal the magnitude of the forces are then equal.

2.3 SYSTEM OPERATION

The function of the Unit is to convert the inlet air pressure, which may be from a regulated or non-regulated pressure source, into an accurately controlled predetermined air pressure which can be used for calibration and checkout purposes.

The Unit outlet pressure, as noted from Figure 1, also pressurizes one end of the rotating piston. The other end of the piston rests upon one end of the beam balance. This pressure imparts a force to the beam through the piston. The relationship then becomes:

(1) $$PA\ell_1 = W\ell_2$$

Where: P = pressure on piston (PSI)

A = effective piston area (square inches)

ℓ_1 = moment arm from piston reaction point to center or main fulcrum on balance (inches)

ℓ_2 = Moment arm from center of weight reaction point to center fulcrum on balance (inches)

W = weight at reaction point on end of balance opposite piston reaction point (pounds)

In a piston-cylinder combination such as used in the balance, the effective area of the combination can be accurately determined by using the mean value of the piston diameter and the cylinder bore.

$$A = \frac{\pi}{4}\left(\frac{p.d. + b.d.}{2}\right) \qquad (2)$$

Where: p.d. = piston outside diameter (inches)

b.d. = cylinder bore diameter (inches)

A = effective area (square inches)

If in Expression (1) above, ℓ_1 is made equal to ℓ_2, as is essentially true for the balance, the equation reduces to:

$$P\,(\pi/4)\left(\frac{p.d. + b.d.}{2}\right) = W \qquad (3)$$

According to this expression P will change proportionately with a change in W. However, other factors, such as pressure and temperature, affect the piston-cylinder combination and change the effective area by some small finite increment. Thus, the relationship of Equation (3) is modified to

$$P = \frac{W}{(\pi/4)(p.d. + b.d.)}(C_1)(C_2) = \frac{W}{A}\,C_1\,C_2 \qquad (4)$$

Where: C_1 = pressure correction factor

C_2 = temperature correction factor

Hence, the force on the piston is directly proportional to the product of the pressure and effective piston area.

Since the force is related to pressure, the beam can be brought into balance by an equal moment reacting on the opposite or weight platform side of the beam. A weight applied to the platform acts as the balance restoring force and may be considered as the input or reference for the balance.

When a weight is first applied to the platform the opposite end of the beam moves upward and actuates the "feed" contacts which in turn energize their respective solenoid valves through a relay. Inlet air pressure is then all into the piston dome and also flows out of the Unit outlet port to the unit undergoing test. As the outlet pressure increases the force exerted by the piston on the beam also increases until at some pressure still below the pressure required by the reference weight or beam equilibrium the beam contactor moves off the "coarse" feed contact and de-energizes the "coarse" feed solenoid valve.

The outlet pressure then rises at a much slower rate until such time as the piston force moment reacts equally with the weight moment thus bringing the beam into balance causing the beam contractor to move off the "fine" feed contact and de-energize the respective solenoid valve.

Outlet pressure in excess of that required by the reference weight causes the rotating piston to exert a greater moment on the beam than exerted by the weights causing the beam to move down and strike the "bleed" contacts. A small unbalance actuates the "fine" bleed solenoid valve while a large unbalance actuates the "coarse" bleed valve. The excess outlet pressure is then reduced until the beam returns to balance deactuating the coarse and fine bleed valves in their respective order.

2.4 COMPONENT GENERAL DESCRIPTION AND FUNCTION IN SYSTEM

The preceding section being somewhat general in nature, does not elaborate upon any of the special features of the various components used in the system. Consequently, a discussion of the particular function for each of the components is in order to more fully explain their operation in the system and to facilitate the comparison between the components noted below and their counterparts in the extended pressure range system.

2.4.1 INLET PRESSURE REGULATOR

This regulator is used in a slightly different fashion than the usual pressure reducing unit. It not only reduces the inlet pressure to the solenoid operated "feed" valves but also maintains a constant pressure differential across the "feed" valves irrespective of the pressure downstream of the solenoid "feed" valves or of the regulator inlet pressure. A schematic of the regulator is shown in Figure 2 which is also represented as a simplified version of the "feed" and "bleed" section of the Balance system.

The regulator poppet is actuated to the open position by spring one which overrides spring two thus allowing the operating media such as compressed nitrogen to flow through the regulator to the solenoid "feed" valve. With the solenoid valves actuated to the open position flow continues through the regulator and valves to ambient pressure or atmosphere. Closing the "bleed" valve allows pressure (P_2 and P_3) to increase in value. As long as the "feed" valve remains open this pressure (P_2 and P_3) will continue to increase until equal to the inlet pressure (P_1). Closure of the "feed" valve with pressure (P_3) at a pressure below (P_1) now effectively isolates pressure (P_3) from the upstream pressure and transforms it into a constant force, which, when combined with spring one continues to hold the regulator poppet open. Pressure (P_2) continues to increase until such time as its reaction against the regulator piston or diaphragm is equal to that of the combined reaction of (P_3) and spring one on the opposite side of the piston. The regulator then closes preventing further flow into the system. At this time pressure (P_2) is higher than pressure (P_3) by a factor equal to the value of the spring load of spring one divided by the effective area of the regulator piston. Thus a differential pressure is established across the "feed" valve. If a restriction is placed in the "feed" valve to limit flow through the valve and if the flow coefficient of the regulator is sufficient so as not to be a limiting factor, the differential pressure ($P_2 - P_3$) can be maintained across the "feed" valve in either its closed or open position over the entire operating range of the Blance. The regulator used in the Balance incorporates a pressure relief provision for the pressure section denoted by (P_2) as shown in Figure 2. Any leakage across the regulator poppet after closure or a change in thermal conditions which result in a further increase in pressure (P_2) causes the regulator piston to move, opens the relief poppet, vents the excess pressure, and returns the pressure to the normal value.

This differential pressure, if maintained at a relatively low value, decreases solenoid valve actuation time, prolongs the life of the poppet sealing surface (trapped volume is less critical), and facilitates control of flow through the valve. Lack of this fixed differential pressure across the solenoid valve results in the valve having to operate at both high and low differential pressures. High differential pressures are detrimental to accurate flow control, as the actuation time for the solenoid valve is increased considerably, and the flow rate through the valve is high.

The schematic of Figure 2 depicts a balanced poppet regulator, however, an unbalanced poppet regulator could also be utilized. With the unbalanced poppet, the minimum differential pressure ($P_2 - P_3$) that can be maintained across the "feed" valve is determined by the spring load of spring one required to open the regulator poppet against the largest differential pressure ($P_1 - P_2$) occurring across the poppet. In practice the inlet pressure (P_1) must be maintained a minimum discrete increment above pressure (P_3). The unbalanced poppet regulator equation is:

$$(5) \qquad P_3(A_p) + F_{s1} = P_2(A_p) + (P_1 - P_2)(A_{pp}) + F_{s2}$$

Where:

A_p = regulator piston or diaphragm effective area

A_{pp} = regulator poppet sealing area

F_{s1} = spring force for spring one

F_{s2} = spring force for spring two

P_1, P_2, P_3 = pressure (PSI)

Then P_3 becomes:

$$(6) \qquad P_3 = \frac{P_1(A_{pp}) + P_2(A_p - A_{pp}) + F_{s2} - F_{s1}}{A_p}$$

If the regulator poppet sealing area (A_{pp}) is small with respect to the area of the regulator piston (A_p), the regulator is of the blanced poppet type, and the force of spring two is small with respect to spring one, the equation reduces to:

$$(7) \qquad P_3 = P_2 - F_{s1}/A_p$$

As (P_3) approaches (P_1) in value, the differential between (P_2 and P_1) decreases and if the flow through the regulator is relatively small, as is the case when only the fine "feed" solenoid valve is open, pressure (P_2) will approach (P_1) in value. Then equation (7) can be modified to:

$$(8) \qquad P_3 \approx P_1 - F_{s1}/A_p$$

Another interesting aspect of the constant low differential pressure across the "feed" valve is that the pressure ratio (P_2/P_3) becomes critical or the flow through the valve is sonic limited only in the very low pressure ranges. For example:

$$(9) \qquad P_3 + P_d = P_2 \quad \text{and}$$

$$(10) \qquad P_c = 0.53P_2$$

Where: P_d = (P_2 - P_3) differential pressure across solenoid valve

P_c = critical pressure for P_3 where flow rate through solenoid valve is independent of downstream pressure

If for the case when (P_3) = (P_c), then

$$(11) \qquad P_3 = 0.53P_2$$

Substituting equation (9) in (11) yields:

$$(12) \qquad P_3 = 0.53(P_3 + P_d) \quad \text{or} \quad P_3 = 1.13\, P_d$$

Hence, assuming that a differential pressure (P_2 - P_3) of 150 PSI is to be maintained across the solenoid valve, the lowest pressure (P_3) that can be attained without the flow through the solenoid valve being sonic limited would be approximately 169 PSIA.

With the fixed differential appearing across the "feed" solenoid valve it is possible to determine the general characteristics of the flow rate through the solenoid valve over the pressure range of the Balance by use of the following equation selected from "Marks Handbook".

$$(13) \qquad w = 2.05C(A_s)P_3 \sqrt{(1/T_2)(P_2/P_3)^{.283}\left[(P_2/P_3)^{.283} - 1\right]}$$

Where: w = air flow through solenoid valve; lbs/min.

C = coefficient of discharge of solenoid valve

A_s = flow area in solenoid valve (sq. ft.)

T_2 = temperature at solenoid valve inlet port (°R)

If T_2 is assumed to be constant under flow conditions (at very low flows only minor temperature changes would occur), the equation can be modified as follows:

$$(14) \qquad w = K_1 K_2 P_3 \sqrt{(P_2/P_3)^{.283} \quad (P_2/P_3)^{.283} - 1}$$

Where: $K_1 = 2.05CA_s$

$$K_2 = \sqrt{(1/T_2)}$$

Analysis of Equation (14) indicates that as pressure (P_3) increases the ratio of (P_2/P_3) approaches unity if the differential pressure (P_2-P_3) across the solenoid valve is small with respect to pressure (P_2) or (P_3). Consequently, the terms outside of the radical become predominate and the function approaches a linear relationship. Evidence of this linear relationship is noted by Figure 3 where the curve of flow rate versus pressure (P_3) is shown. Values for this curve were taken from Table I. This also tends to verify the linear characteristics for the fine "feed" valve used on the Balance as shown by Figure 4.

2.4.3 FEED-BLEED SOLENOID OPERATED VALVES

The solenoid valves are used to control the flow of the operating media into and out of the surge tank in the Balance. Actuation of the valves is through a sensitive relay which is energized by the moving contact on the beam of the Balance completing the circuit with the respective fixed contact on the frame of the Balance.

The valves are standard commercial units which have been modified to incorporate a fixed orifice and special welded fittings on the ports to facilitate mounting and tube connections. The fixed orifice of the "fine" feed and bleed valves is essentially a long length of capillary tube. This yields a very small effective flow area and provides the necessary low flow rate through the valves. The coarse feed and bleed valves utilize the variable orifice supplied with the valve. The modifications to the basic valve are quite extensive with both machining and welding of the valve body required. The basic valves are rather inexpensive in price (below $15.00) thus making the modification attractive.

2.4.4 PISTON-CYLINDER COMBINATION

The piston cylinder combination consists of a rotating piston housed in a cylinder and provides a very effective device for converting pressure to force and axial movement, with a minimum of friction and no spring force. As is shown by Figure 1, the piston acts as the reaction load for one side of the beam on the Balance.

The rotating piston in the Balance consists of a standard commercial piston-cylinder combination, modified as required, to provide a means of mounting the unit to the bottom of a small pressure dome. The dome is supported from the frame of the Balance by three cylindrical posts and provides a small reservoir for oil, which serves to lubricate and act as a pressure seal between the wall of the cylinder and the piston. Diameter of the piston is about 9/32 of an inch yielding an effective pressure area about 1/16 of a square inch. The piston material is corrosion resistant steel and the cylinder material is brass. The lower end of the piston has been modified to incorporate a gear and a housing or seat for a 1/8-inch-diameter steel ball. The ball acts as a modified pivot bearing and bears directly against a hardened plate located on the beam of the Balance. The gear on the piston is used to provide the means of rotating the piston to reduce friction during axial movement. The gear is connected to an electric motor located beneath the base of the Balance, through a small gear train and a flexible shaft.

2.4.5 FEED-BLEED CONTACTS

The contacts for actuating the relays, controlling the solenoid valves in the system, consist of a single moving contact located on the beam of the Balance and two pairs of semi-fixed contacts located on the Balance frame as shown schematically by Figure 1.

The two pairs of semi-fixed contacts straddle the single moving contact on the beam of the Balance. The first pair of contacts immediately adjacent to the single moving contact are the controlling elements or switches in the electrical circuit for either the "fine" feed or bleed solenoid valves in the system. The "fine" feed solenoid valve is energized when the moving contact on the beam touches the upper contact and completes the electrical circuit to the respective valve. The "fine" bleed solenoid valve is energized when the lower contact is touched by the contact on the beam. The distance that the center moving contact must travel to alternately energize the "fine" feed and bleed valves is denoted as the "dead band" of the Balance pressure regulating system. An adjustment is provided on each set of contacts adjacent to the center moving contact to vary the spacing or distance between the two contacts. Consequently, the "dead band" of the system can be varied by this adjustment thus increasing or decreasing the sensitivity of the Balance. As can be noted from the above, if the sensitivity of the Balance is very high, the use of the contacts does not degrade the performance since the electrical circuit controlling the valves can be closed by the contacts just coming in touch with each other.

The additional pair of contacts make up the switching elements for the "coarse" feed and bleed solenoid valves. A pressure deviation in excess of that required to move the beam contact to either of the fine contacts causes the beam contact to move the fine contact pin back against a spring and allow the pin to touch the second contact and close the electrical circuit to the respective "coarse" feed or bleed solenoid valve. An adjustment is provided on the second pair of contacts to vary the pressure deviation between the actuation points of the "fine" and "coarse" solenoid valves.

2.4.6 SURGE TANK

The surge tank in the system is used as an integrating or damping device. It functions in the same manner as a capacitor in a DC power supply to reduce ripple in the output. The damping volume of the tank should be sufficient to provide smooth operation of the system with the abrupt start and stop of input and output of air flow such as experienced with an on-off or "bang-bang" type of system. It also helps to minimize effects of "trapped volume".

3. SYSTEM CONFIGURATION AND OPERATION (5,000 PSI SYSTEM)

3.1 SYSTEM CONFIGURATION

The modified or extended pressure range (0 to 5,000 PSIG) Balance utilizes the principle of operation shown schematically by Figure 5. As can be noted by comparing Figures 1 and 5, the basic system configuration for the two Units is identical with the exception that the extended range Unit incorporates four additional items. Two of the added components are a back-pressure regulator used across the bleed valves and a three-way solenoid operated valve used as a sequencing control on the dome of the inlet pressure regulator. The other two remaining parts are filters which provide contaminate protection for the operating components in the system.

3.2 SYSTEM OPERATION

The principle of operation is identical to that of the low pressure Balance. The refinements to the system consist of the addition of a three-way solenoid valve to improve system response time in the feed mode and utilization of a back pressure regulator across the bleed valves to provide flow characteristics for these valves similar to that of the feed valves.

The back-pressure regulator maintains essentially a constant pressure differential across the bleed valves throughout the pressure range of the Balance in much the same manner as provided for the feed valves. This fixed differential pressure, approximately equal to that maintained across the feed valves, establishes approximately the same flow and operating characteristics for both the "fine" feed and bleed solenoid operated valves. Without the fixed differential pressure across the bleed valve, actuation time for the bleed valve will vary over the operating pressure range, trapped volume becomes a major factor, and valve seat life is drastically reduced. Information obtained from various valve suppliers indicated that the valve poppet seat life at pressures of 5,000 to 6,000 PSIG to be approximately 15% of that at pressures of 3,000 PSIG and below. Another feature of the back-pressure regulator which is immediately evident is the high degree of silencing produced by the regulator on the gas exhausting from the bleed valves to the atmosphere. Without the regulator, the noise level resulting from venting the high pressure gas directly to the atmosphere, is very high.

The three-way solenoid operated valve connected to the dome of the inlet pressure regulator provides a third mode of operation for the feed system of the Balance in addition to the "coarse" and "fine" feed modes also used on the low pressure Balance. A separate switch located on the frame of the Balance is actuated subsequent to closure of the "fine and coarse" feed contacts when a sufficient weight differential is placed on the weight platform. The actuation of this switch energizes the three-way solenoid valve changing the porting to the dome on the inlet pressure regulator from the low pressure side of the two feed solenoid valves to the inlet side of the regulator. This effectively disables the regulator by forcing the poppet to the full open position and places the Balance inlet pressure directly on the inlet of the solenoid feed valves. Consequently, the flow through the "coarse" and "fine" feed valves is increased to a maximum, thus resulting in an increase in the response time for the system by several orders of magnitude. As the pressure downstream of the feed valves increases the reaction on the beam of the Balance from the rotating piston also increases and moves the beam away from the switch controlling the three-way valve when a pre-set pressure differential is attained. With the switch de-actuated, the three-way valve is again de-energized and the inlet pressure regulator becomes effective.

3.3 COMPONENT DESCRIPTION AND FUNCTION IN SYSTEM

3.3.1 INLET PRESSURE REGULATOR

The inlet pressure regulator used in the low pressure Balance had an operating pressure of 6,000 PSIG. Consequently the regulator could also be used in the extended pressure range Balance as its function is identical to that in the low pressure system. This particular unit is a modified model RV44P regulator manufactured by Marotta Valve Corporation under part number 223994.

3.3.2 BACK PRESSURE REGULATOR

As noted previously, the purpose of this additional regulator in the system is to maintain a constant differential pressure across the bleed solenoid valves in much the same manner as provided on the feed valves. Investigation of the various commercial regulators available indicated a standard unit did not appear to be available. However, it was noted the inlet regulator was such that it could be used as a back pressure regulator when modified to incorporate a new piston of different configuration and a new spring to bias the regulator piston opposite to that for the inlet regulator. The configuration for the back pressure regulator is shown schematically by Figure 6. A bleed valve is also shown to represent a simplified version of the bleed section of the system.

A comparison of the regulator schematics of Figures 2 and 6 indicate the regulators to be identical with the exception of the position of springs one and three. Spring one is located in the cavity of the inlet regulator designated as P_3 while spring three is located in the pressure cavity designated as P_4 (this is the same cavity noted as P_2 in the inlet regulator). The inlet regulator poppet is biased to the open position with the relief poppet closed while the back pressure regulator poppet is biased to the closed position with the relief poppet open.

With the feed valve closed and zero pressure at P_3, spring three forces the piston away from the regulator poppet as shown by Figure 6. Spring two then causes the regulator poppet to close. With the piston forced away from the regulator poppet the relief poppet is opened venting the cavity designated P_4 to atmosphere.

Opening the feed valve and closing the bleed valve causes pressure (P_3) to increase until such time as the force of (P_3) on the regulator piston overrides the force of spring three and causes the piston to seat on the relief poppet. As pressure (P_3) continues to increase the force on the piston exceeds that of the combined forces of springs two and three and the regulator poppet opens allowing pressure into the cavity designated as (P_4). Any further increase in pressure (P_3) subsequent to the opening of the regulator poppet causes a corresponding increase in (P_4).

With pressure at (P_3) and the feed valve closed, the spring and pressure forces on the regulator regain equilibrium and the regulator poppet closes thus isolating pressure (P_4) from the rest of the system. At this time pressure (P_3) is higher than pressure (P_4) by a factor equal to the value of the spring load three divided by the effective area of the piston. Thus a differential pressure is established across the bleed valve.

With this differential pressure across the bleed valve, opening the valve causes pressure (P_4) to increase. When combined with the force of spring three this increase in pressure causes the piston to move, opens the relief poppet and vents pressure (P_4) to atmosphere. If the flow through the bleed valve is much less than that possible through the relief section of the regulator, as in the case of the "fine" bleed valve, the pressure differential (P_3 - P_4) can be maintained nearly constant. If the flow capability of the valve is greater than that of the regulator relief section, the regulator will be the governing unit and the pressure differential across the valve will vary from a maximum at no flow to a minimum during flow.

The unbalanced poppet back pressure regulator equation is:

$$(16) \quad P_3 A_p = F_{s3} + P_4 A_p + (P_3 - P_4)\ (A_{pp}) + F_{s2}$$

Where: P_3 = pressure at rotating piston & surge tank (PSIG)

P_4 = pressure downstream of bleed valve (PSIG)

A_p = regulator piston effective area (sq. in.)

A_{pp} = regulator poppet sealing area (sq. in.)

F_{s2} = spring force for poppet spring two

F_{s3} = spring force for regulator piston three

Then P_4 becomes:

$$(17) \quad P_4 = P_3 - (F_{s3} + F_{s2})/(A_p - A_{pp})$$

If the regulator poppet sealing surface (A_{pp}) is small with respect to the regulator piston area (A_p), or the regulator is of the balanced poppet type, and the force of spring two is small with respect to spring three, the equation reduces to:

$$(18) \quad P_4 = P_3 - F_{s3}/A_p$$

Comparing Equation (18) with (7) indicates the form of the equation to be identical. Hence, the differential pressures ($P_3 - P_4$) and ($P_2 - P_3$) are a function of the loads of springs one and three. If the two springs are equal then the differentials across the feed and bleed valves will be equal.

It should be noted that in the derivation of equations (7) and (18), the relief poppet sealing area and the friction of the O-ring seal used on the regulator piston was neglected. In the particular regulator used in the Balance the relief poppet sealing area was essentially "balanced" and very small with respect to the regulator piston and could be neglected. Also in the true unbalanced poppet regulator, the relief section is generally not incorporated. For a diaphragm type regulator an O-ring seal is not utilized. However, in the piston-type, an O-ring seal is required on the piston. The characteristics of this type of seal are such that at high pressures friction becomes a major part of load for the spring. This was particularly noticeable in the design of spring three where a low differential pressure of about 30 PSI was initially established in order to minimize both trapped volume and pressure drop across the bleed valves. The back pressure regulator functioned properly to about 2200 PSIG at which pressure it failed to vent. Progressively increasing the spring load until an approximate differential of 70 PSI was attained solved the problem. Consequently, at low differential pressures and high operating pressures, O-ring friction, even at very small piston travels, should enter into the regulator equation.

The leakage characteristics of the back pressure regulator are of much greater significance than those of the inlet pressure. A small leakage path across the poppet on the inlet regulator is compensated by a partial opening of the relief valve thus maintaining pressure (P_2). A leak in the relief section of the inlet regulator is readjusted by opening of the poppet. This condition is not true of the back pressure regulator in that it is essentially in parallel with the bleed valves.

Consequently, extremely low leakage characteristics are mandatory for the back pressure regulator.

As noted previously, a Marotta Valve Corporation 223994 regulator was modified to function as the back pressure regulator. Additional investigation indicated an alternate Marotta 213453 regulator could be modified and used as the back pressure regulator. This alternate is less expensive from both a unit and modification cost standpoint.

3.3.3 FEED-BLEED VALVES

The valves used in the low pressure Balance were rated at 3,000 PSIG body working pressure and approximately 250 PSI differential pressure across the poppet seat. These valves could not be used in the extended range Balance and were replaced by valves rated at 6,000 PSIG operating pressure.

Standard 6,000 PSIG valves incorporating an integral variable metering device did not appear readily obtainable. Special valves were found to be available; however, delivery time, cost, or type of poppet seal did not make these units attractive. Also, modifying a high pressure valve to incorporate integral metering did not appear too attractive due to the somewhat complex type of modification required and the risk of damage to a relatively expensive unit during modification. Consequently, with the low differential pressure maintained across the valves, it appeared that an external variable orifice could be used on a standard high pressure valve if the variable orifice was located close to the valve poppet seat. The valve and its external orifice is shown by Figure 7. As can be noted the volume between the valve poppet seat and the variable orifice is not as small as could be obtained with integral metering. However, this volume did not appear to affect system performance to any great extent. The incorporation of the external orifice allows the use of a standard solenoid valve without modification.

3.3.4 PISTON-CYLINDER COMBINATION

The piston-cylinder combination on the low-pressure Balance utilized a piston with an approximate effective area of 1/16 square inch. This area would require weights totaling about 312 pounds to achieve 5,000 PSIG pressure. Therefore, the high pressure Balance incorporated a new piston cylinder combination of about 1/80 square inch which requires about 62.5 pounds on the weight platform to achieve 5,000 PSIG pressure. Consequently, the weight loading for the two systems would be the same.

The configuration for the mounting of the new piston-cylinder assembly is similar in nature to that used on the low pressure system. The dome for the low pressure system was replaced with a new dome suitable for 5,000 PSIG pressure. A Manning, Maxwell, and Moore, Inc. LA1000A piston was modified as required for mounting to the pressure dome and to incorporate the rotational drive provision.

The gear on the rotating piston is connected to a small electric motor located adjacent to the pressure dome through a short gear train and an O-ring drive. This type of installation replaced the large motor located beneath the frame of the Balance thus providing space for the four added components in the system. Placing the motor adjacent to the pressure dome reduced the motor power requirements by eliminating the flexible shafting. A considerable reduction in motor size was then possible. The motor used in the high pressure Balance was a Globe Industries, Inc. 75A120-1 Induction Motor. Any similar motor could also be used.

It was noted during the evaluation of the low pressure Balance that the 1/8 - inch diameter steel ball affixed to the end of the piston was indenting the hardened plate on the beam of the Balance. A subsequent stress analysis indicated point contact stresses well in excess of the material capabilities thus confirming the brinnelling on the plate. In addition, it was also indicated that with no lubrication the ball would seize or adhere to the hardened plate at loads of about 35 pounds and above. This phenomena would cause permanent deformation of the ball. If an extension of the pressure range for the high pressure Balance were to be contemplated, this particular area would require modification to prevent permanent deformation and damage to the ball.

3.3.5 FEED-BLEED CONTACTS

The contacts on the low pressure Balance were incorporated directly into the high pressure Balance. An additional set of contacts in the form of a snap-action switch was added to the high pressure Balance to provide a third mode of operation on the feed cycle as previously described.

3.3.6 SURGE TANK

The surge tanks in both the high and low pressure system perform identical functions. The tank used in the low pressure system appeared to have been rated at about 7,000 PSIG, however, the flared tube fittings on the ports had been used considerably as evidenced by deformation of the sealing surfaces on the ports. Consequently, an accumulator of approximately the same size incorporating threaded female bosses was adapted for use in the system to minimize possible port damage test of the Balance. Volume for the surge tank in the low pressure unit was approximately 23 in^3. The volume for the high pressure is about 33 in^3.

3.3.7 THREE-WAY VALVE

This unit is a standard three-way solenoid operated valve rated for 6,000 PSIG operating pressure. Any commercial unit is satisfactory for use if the leakage characteristics are extremely low and the operating voltage is compatible with the other valves in the system. For this particular application a Marotta Valve Corporation 209603 valve is used.

3.3.8 FILTERS

Low or zero leakage across the valves and regulators in the system is one of the criteria for proper operation of the system. Contaminate introduced into the system could easily damage the sealing surfaces on the valves and regulators. Consequently, two 10-micron line mounted filters were introduced into the system to minimize contamination of the system. One filter is mounted on the inlet to the Balance and the other is mounted in the outlet or controlled pressure line.

4. EVALUATION TEST SUMMARY

4.1 EVALUATION TEST SETUP

The high pressure Balance was installed in a test setup similar to that shown schematically by Figure 8 with the outlet port of the Balance connected in parallel to a Heise pressure gage and a Ruska Model 2400.4 dead weight tester. In general, all tests were conducted using this test setup. The testing for the Balance consisted of a leakage and stability test, resolution test, and response test.

4.2 LEAKAGE AND STABILITY TEST

This phase of the testing consisted mainly of checking the system for leakage and stability under increasing pressure conditions. The switch controlling the third mode of operation on the feed system was not installed at this time in order to establish the characteristics for the basic feed-bleed system. At the conclusion of the tests, the system was stable across the pressure range and leakage had been essentially eliminated except for intermittent leakages across the seats of the valves and regulator poppets.

Problems encountered during this phase of the test consisted of leakage, back pressure regulator vent failure, system oscillation, and resolution irregularities.

4.2.1 LEAKAGE

This was essentially the same problem encountered in all high pressure systems utilizing tubing, fittings, and valves. Correcting a leakage condition was not as much of a problem as locating the leak since the majority of the tubing runs and all the valves in the system are located beneath the frame of the Balance from both a safety and packaging standpoint. The valves and regulators proved to be the main offenders with irregular leaks occurring throughout the test. This necessitated removing the unit from the system, disassembling it, and then checking the seals for damage. Only two instances of seal damage were noted where seal replacement was required. It appeared that minute particles of contaminate introduced into the system during assembly caused the majority of the problems. During the latter phase of the testing, seal leakage appeared to be almost negligible.

4.2.2 BACK PRESSURE REGULATOR

The only major problem occurring with this unit was that of piston seal friction which prevented venting at the higher pressures. Increasing the spring load eliminated the problem, however this required the fabrication of new springs.

An external spring adjustment would have facilitated determining the correct spring load, however this type of adjust was not particularly feasible on the unit. Consequently, disassembly of the unit was required each time the spring was changed during the development stage.

4.2.3 SYSTEM OSCILLATION

In the initial phases of the testing some oscillation of the beam was evident when attempting to stabilize at a set pressure. This oscillation could be controlled almost entirely by the adjustment of the "fine" feed or bleed variable orifices and did not appear to be a function of the contact spring load or rate. Consequently, the period of oscillation could be increased to a relatively large value at a very small resolution over the entire pressure range.

4.2.4 RESOLUTION IRREGULARITIES

Irregularities of resolution were evidenced during the initial evaluation of the low pressure Balance and would occur subsequent to placing the Balance on its back surface as generally required to gain access to the plumbing contained beneath the frame. When the Balance was again placed in the operating position a zero shift would be noted and the resolution would increase by several magnitudes. This appeared to be caused by a lateral shift in the position of the center knife edges in their grooves. The cause for this shift was not apparent but appeared to be resulting from the ball on the rotating piston falling into one of the several indentations in the plate. If the indentation did not allow for proper alignment of the knife edges in their grooves a small amount of binding appeared to occur. Several indentations in the plate were in evidence and were attributable to a shift in the dome position during various assemblies. The position of the dome is determined only by bolts, consequently, a shift from assembly to assembly can be realized. By moving the Balance beam slightly a new position for the ball would be found where the zero and resolution returned to the previous values.

4.3 RESOLUTION TEST

Resolution is defined as the smallest change in weight on the platform that will produce a measurable change in the equilibrium of the Balance.

For this test the outlet of the Balance was connected directly to the Ruska dead weight tester. The resolution tests were conducted at pressures of approximately 500, 1,000, 2,000, 3,000, 4,000, and 5,000 PSIG.

Weights were placed on the Ruska corresponding to the pressure desired. Weights were then added to the platform of the Balance until floatation of the Ruska weights was noted. During these tests it was noted that it was possible to "float" the Ruska at the midpoint of its piston travel. This resolution of the Balance was in evidence through the entire pressure range. The resolution of the Ruska is given as a maximum of 5 PPM. Consequently, the Balance resolution appeared equal to that of the Ruska. Stabilization time for the Ruska appeared to be about 15 minutes.

The "dead band" for the Balance during this test was 0.005 inch. Due to the small increments of pressure being considered, there was some cycling of the "fine" feed and bleed solenoid valves during the test at the various pressure settings. At the higher pressure the predominance of feed cycling is attributable to leakage in the Ruska and in the associated plumbing. Table 2 indicates the degree of cycling at the various pressures.

A second resolution test was conducted for personnel of the Contracting Agency. This test differed from the previous test in that the Balance was brought into equilibrium at a given pressure. Weights were then added to the weight platform to determine the increment weight required to disturb the equilibrium condition to the extent that either the "fine" feed or bleed solenoid valves were actuated. The outlet port of the Balance was capped in lieu of being connected to the Ruska and pressure gage. For this particular test, a pressure of 2,000 PSIG was selected and weights yielding this pressure were added to the platform of the Balance. When equilibrium was achieved, as indicated by no cycling of the feed-bleed solenoids, small weights were added until the feed solenoid was actuated. This was then repeated on the opposite side of the beam to actuate the bleed solenoid and achieve an average value of the weight. It was found that one (1) gram would not cause actuation whereas two (2) grams would cause immediate actuation. This yields a resolution of:

$$\frac{(0.002205\ \#/\text{gram})\ (2\ \text{grams})}{(2{,}000\ \#/\text{sq.in.})\ (1/80\ \text{sq.in.})} = 0.0176\%\ \text{or}\ 176\ \text{PPM}$$

This indicates a resolution several magnitudes greater than previously noted. Prior to this test the Balance had been placed on its side to allow viewing of the plumbing and control system. Upon returning to the upright position, operation appeared normal, however it was noted that when the Balance was reconnected to the Ruska, floatation of the Ruska weights was not possible. The second resolution was then conducted. Therefore, it appears the knife edges were again out of alignment to some extent. However, even this magnitude of resolution is considered quite satisfactory and would yield a resolution of 0.007% at 5,000 PSIG if no additional friction were induced into the Balance from the added weights on the Balance.

4.4 RESPONSE TIME

The response time for the system is defined as the time for the system to move from one established condition to a new given condition. The response time is dependent upon the flow characteristics of the feed-bleed valves and regulators. This test was conducted with the Balance in a setup shown schematically by Figure 8 with the exception that only the pressure gage was connected to the outlet or controlled pressure fitting.

The test consisted of determining the response time for three separate modes of operation, namely, "coarse" feed, "coarse" bleed, and "fast" feed. The last mode is induced by the three-way valve. The response time test for the "fine" feed and bleed modes was not conducted, as the response time for these modes is considered a secondary function, with control considered as the primary function.

4.4.1 COARSE FEED RESPONSE

This test consisted of placing a given weight on the platform of the Balance, actuating the main toggle switch of the Balance, and then observing the time span from the actuation of the toggle switch to the extinguishing of the "coarse" feed indicator lamp on the front of the Balance. The contacts were set to obtain about a 25 PSI differential pressure between the deactuation of the "coarse" feed solenoid valve and the "fine" feed solenoid valve. Results of the test are shown on Figure 9.

4.4.2 COARSE BLEED RESPONSE

This test consisted of allowing the Balance to stabilize at the high pressure end of the range and then to suddenly remove all of the weights on the platform. Time was recorded at various pressure increments to establish the pressure decay curve shown by Figure 9. This is a typical curve for an orifice.

4.4.3 FAST FEED RESPONSE

The snap action switch for actuation of the three-way valve controlling this mode of operation was added subsequent to conducting the previous tests. Plumbing difficulties prevented the witnessing of this test by personnel of the Contracting Agency.

This test was conducted in the same manner as for the "coarse" feed response test. Since the overshoot could not be defined accurately, the spread between the "fine" and "coarse" feed actuation points was increased to about 75 PSI in lieu of 25 PSI. The results are shown on Figure 9. As can be noted, the response time for the system was decreased by nearly a factor of four by the addition of the third "feed" mode of operation.

5. SUMMARY

5.1 GENERAL

The modification to the Balance indicated a stable, extremely sensitive unit was possible over a pressure range extending to 5,000 PSIG. The principle of the basic Balance was carried over into the extended range unit, thus providing a relatively uncomplicated piece of equipment that exhibits good reliability, high resolution, ease of calibration, and good maintainability. Tests and observations indicated that further modifications could be incorporated in the following areas.

5.2 CONTACTS

The semi-fixed contacts located on the frame of the Balance proved erratic in operation and would cause the Balance to "overshoot" occasionally in the "fine" feed or bleed mode. This is attributed to the discontinuities and warped surfaces of the contacts used in this particular Balance. Also, contact binding proved to be a considerable problem. Both of these conditions appeared to be caused from wear of the contacts through prolonged usage. The basic concept for the contacts leaves little to be desired and modifications incorporated would be to improve operation. The snap-action switch for the three-way valve would be mounted to the body of the upper pair of contacts and be actuated by the shaft on the "coarse" feed contact.

5.3 INTERCHANGEABLE PRESSURE DOMES

System stability indicated the possibility of extending the pressure range well beyond 5,000 PSIG. One Balance, utilizing several interchangeable pressure domes incorporating selected piston sizes, could be used to cover a wide range of pressures by interchanging domes. Piloting of the dome by means other than bolts would position the rotating piston and minimize variations now possible with the existing design.

The interface between the ball on the rotating piston and the hardened plate on the beam of the balance is such that the point contact stress on the ball and plate is well in excess of that allowable, causing brinnelling of the hardened plate in the form of a slight indentation. This indentation, while lowering the stress, increases friction on the ball and requires that the ball seat precisely the same each time the dome is removed and reinstalled or the beam on the Balance is moved during handling.

5.4 ARC SUPPRESSION

The solenoid valves in the system are energized by sensitive relays which in turn are energized by the contacts on the Balance frame and beam. The valves and relays are inductive loads and as such are capable of providing a very high voltage across the relay contacts while the contacts are breaking the circuit. The arc produced by this "inductive kick" decreases the life of the contacts and adds a short delay in breaking the circuit. Diodes or other suitable elements incorporated into the electrical circuitry would provide the required degree of arc suppression.

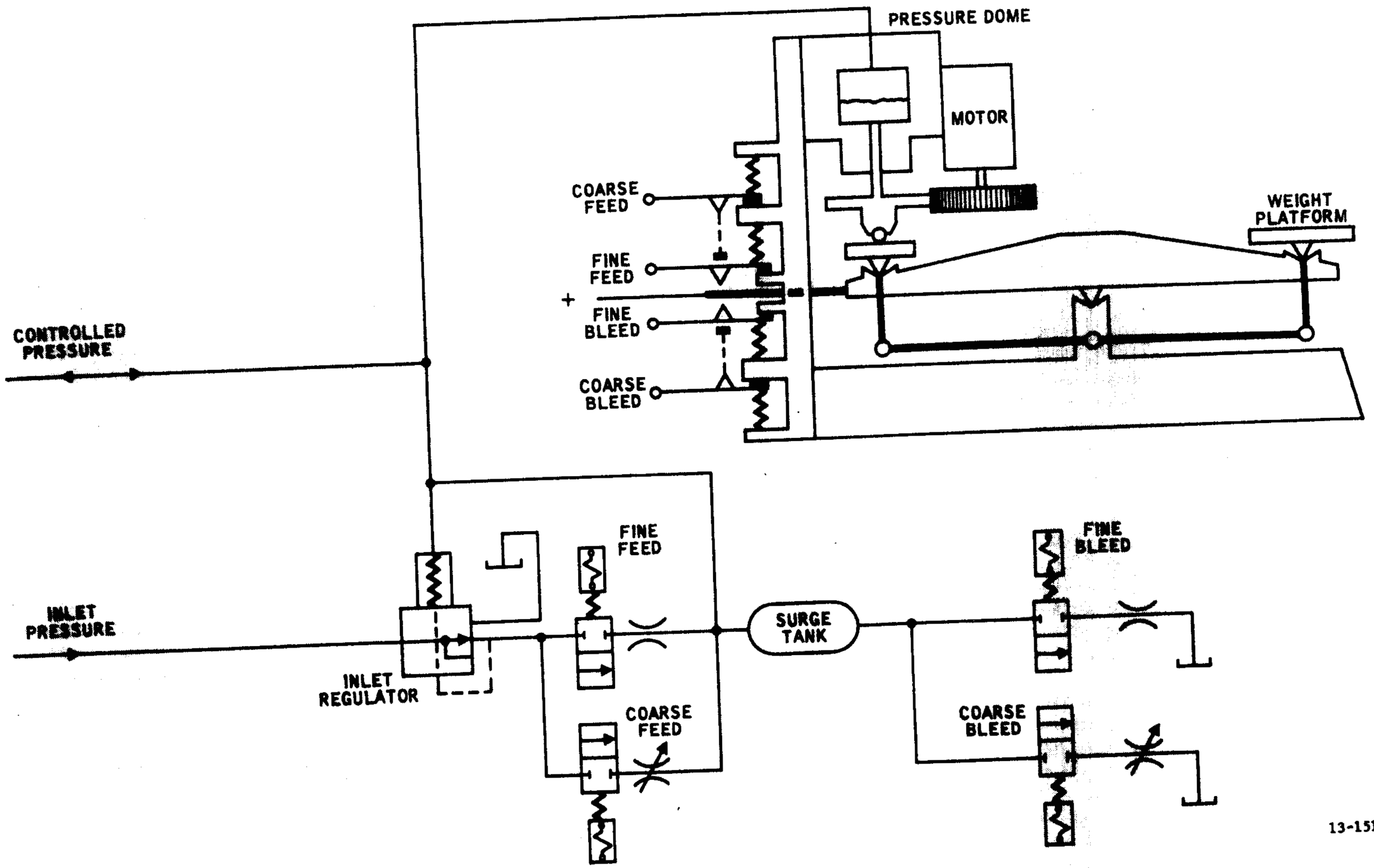

FIGURE 1
Schematic - Dead Weight Pressure (Schuler) Balance

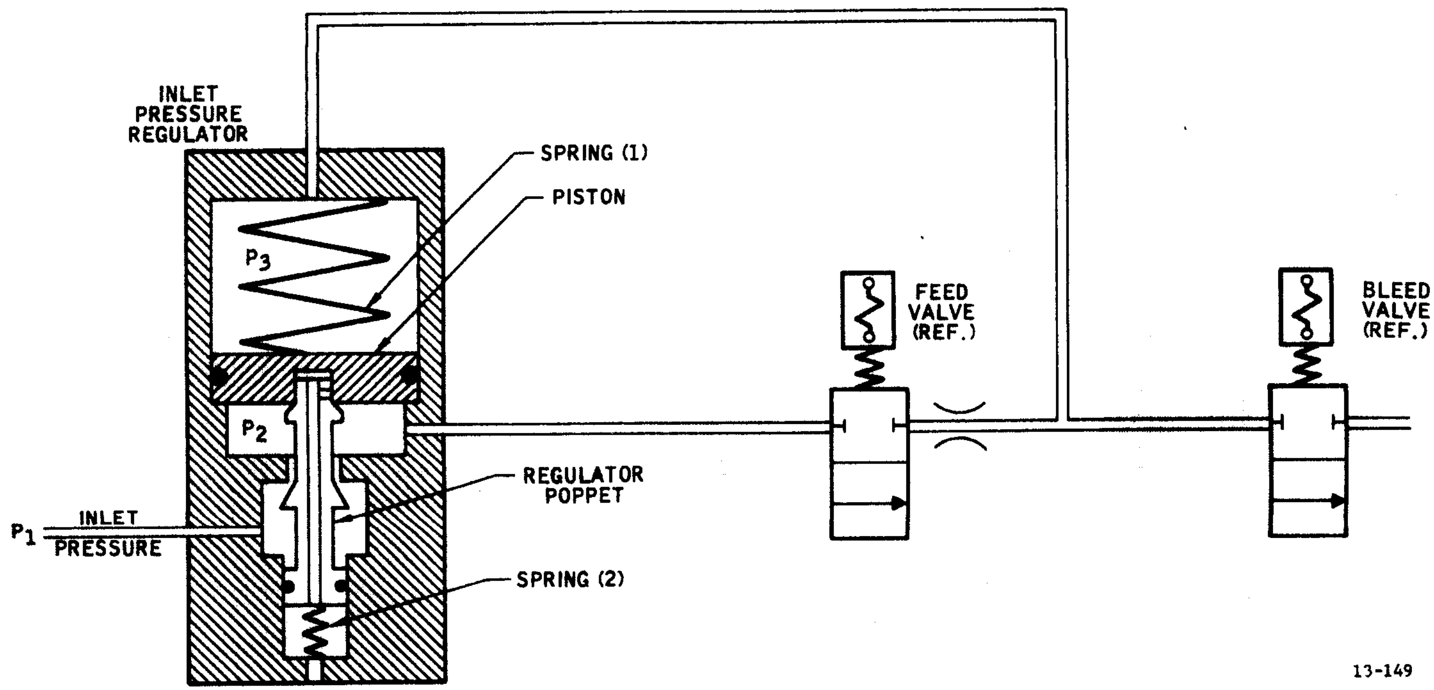

FIGURE 2
Schematic - Inlet Pressure Regulator

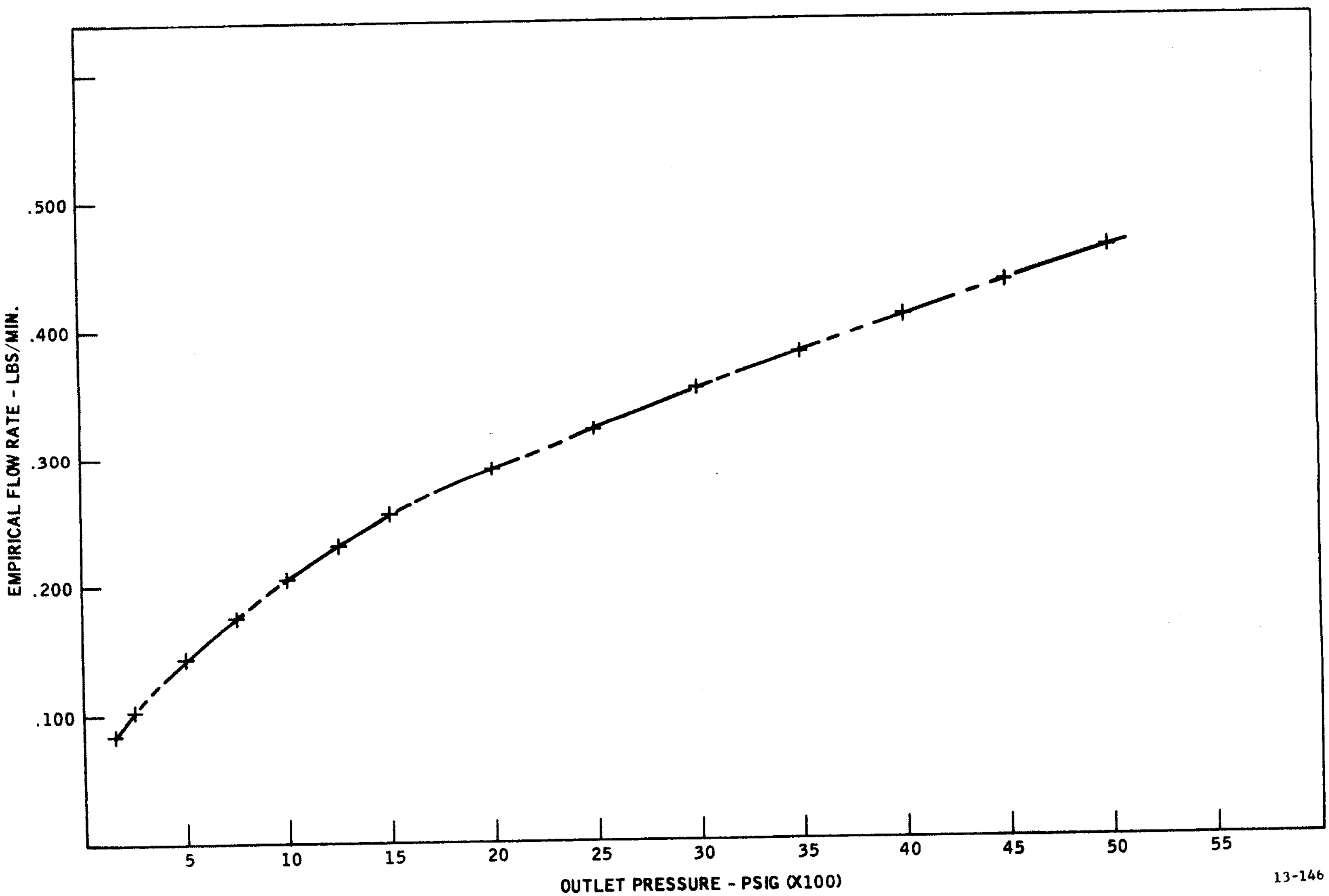

FIGURE 3
Outlet Pressure - PSIG (X100)

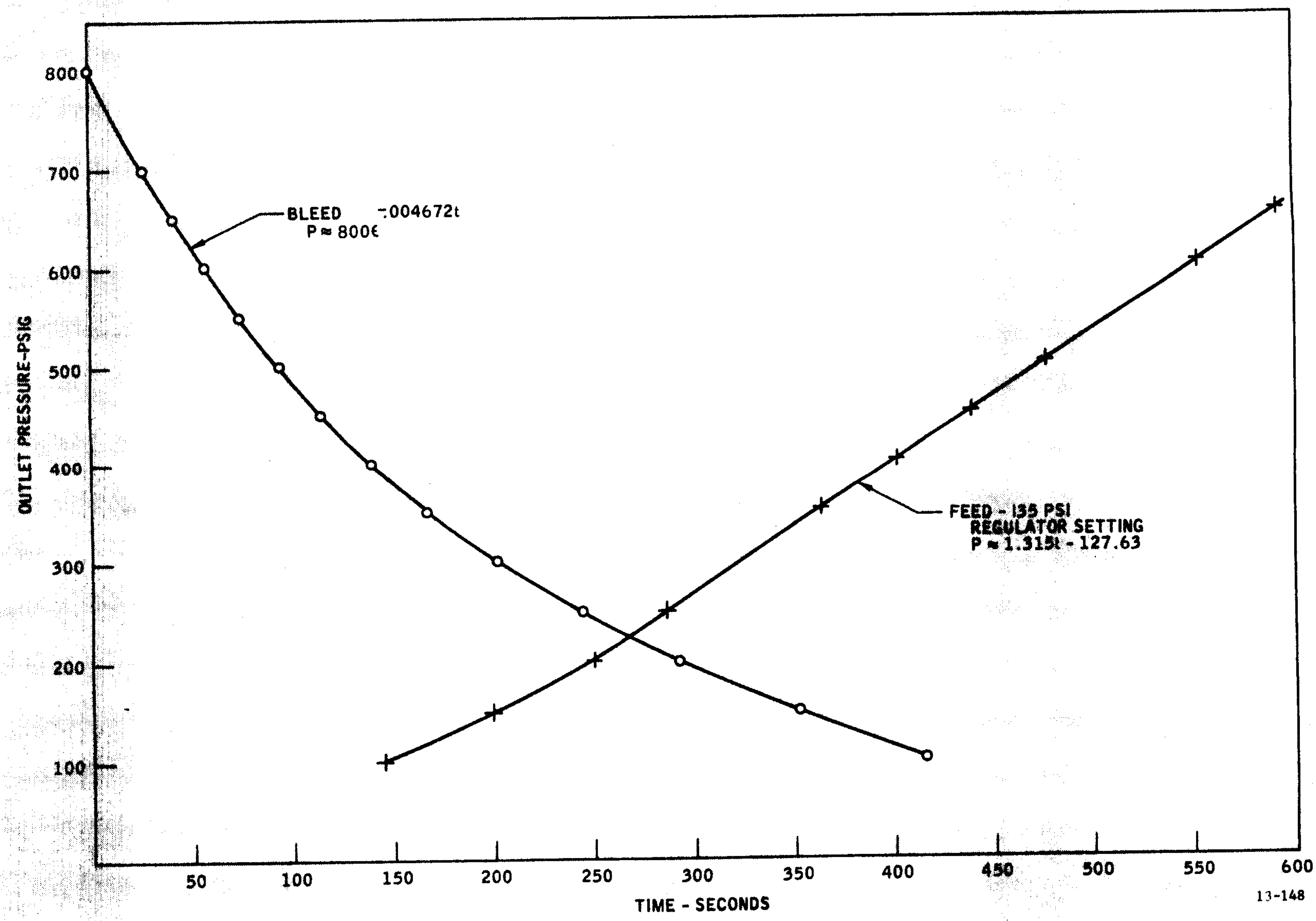

FIGURE 4
Fine Feed - Bleed Solenoid Valves Flow Characteristics,
(Low Pressure Balance)

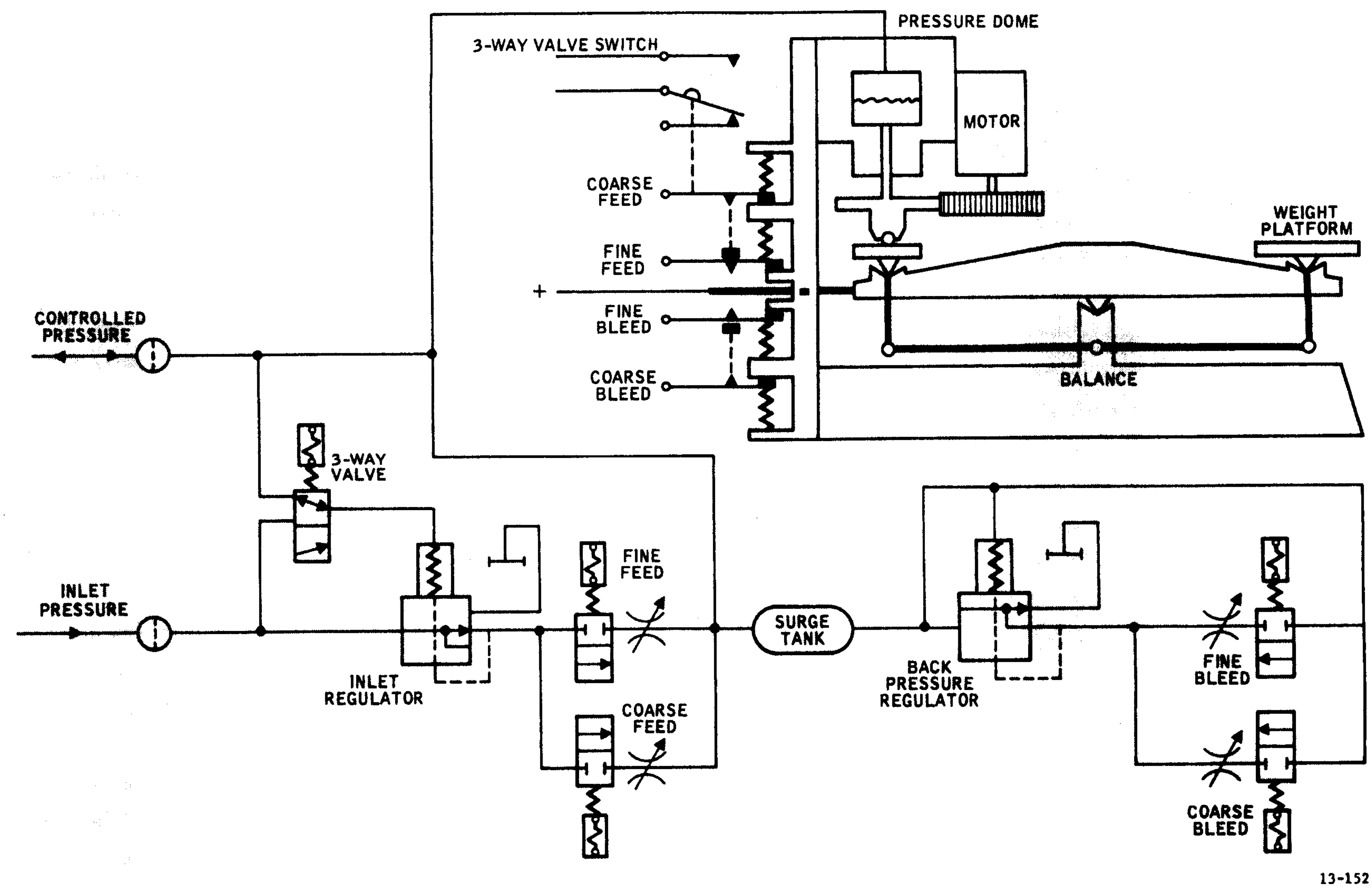

FIGURE 5
Schematic - Extended Range Dead Weight Pressure Balance

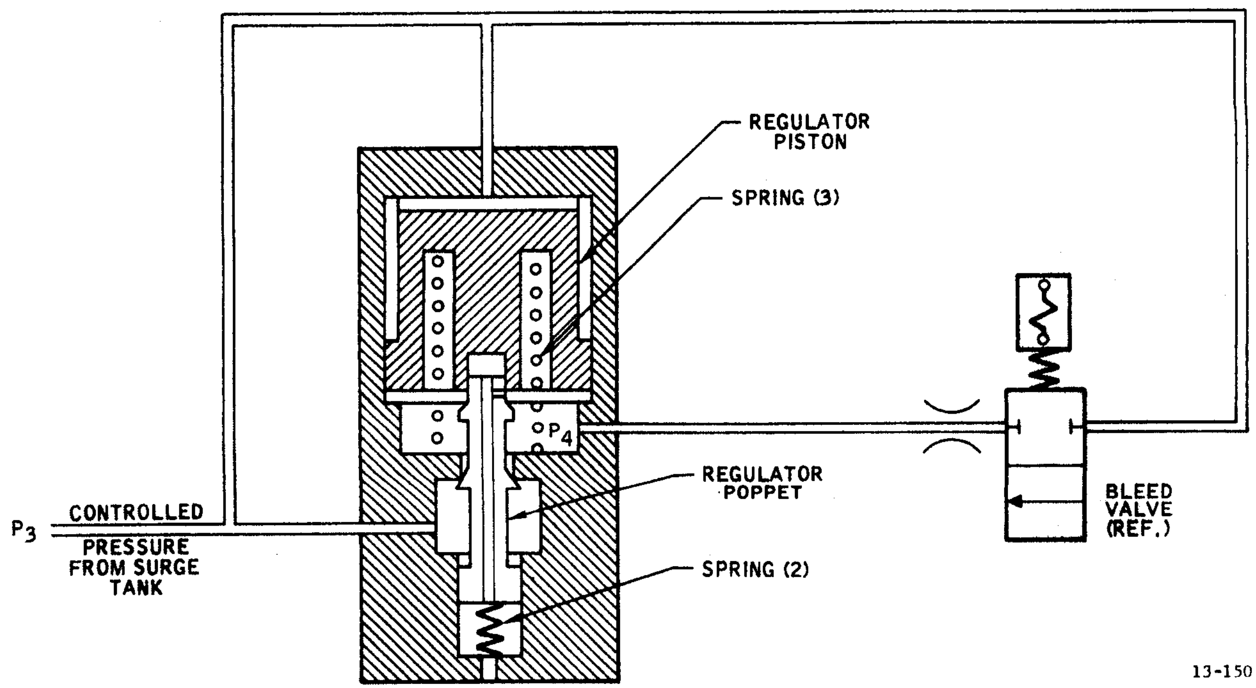

FIGURE 6
Schematic - Back Pressure Regulator

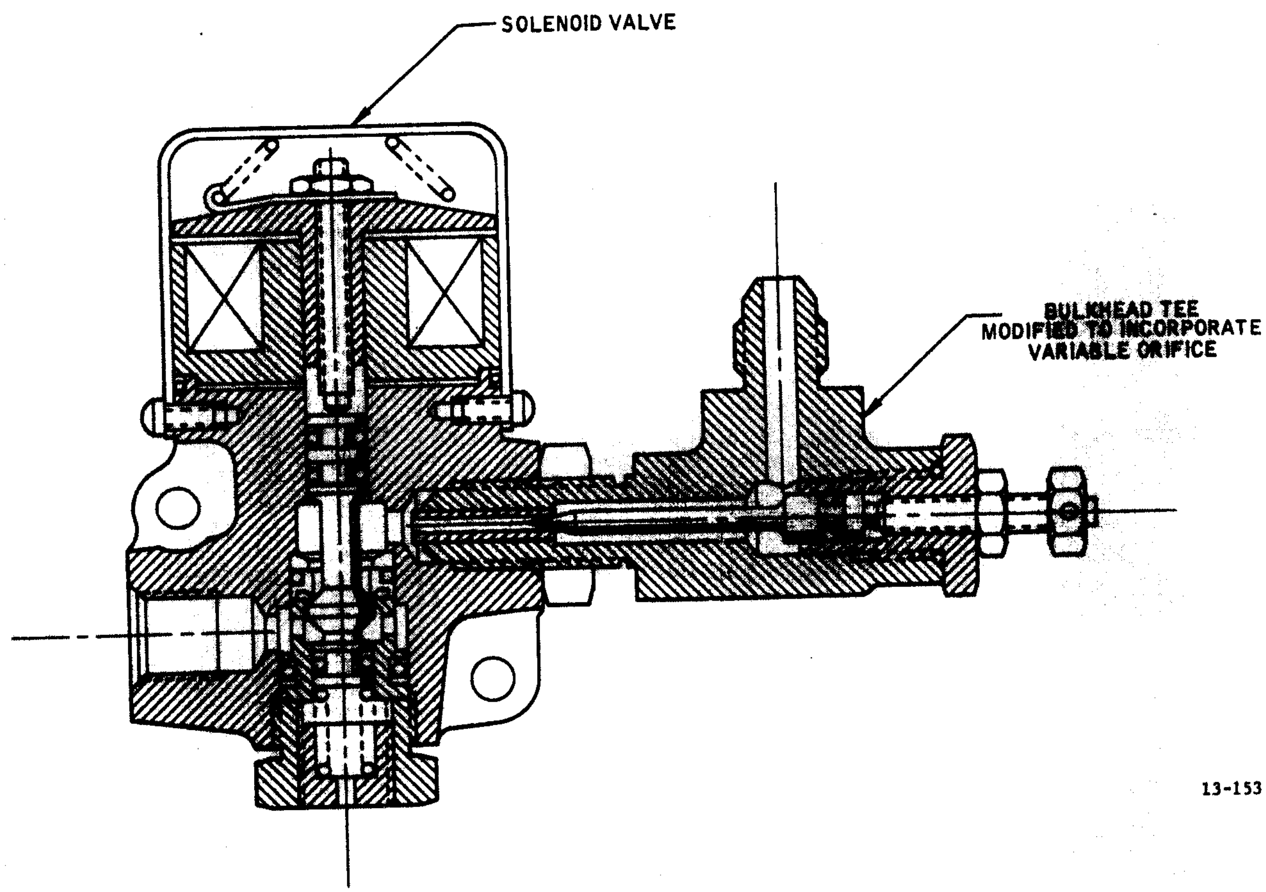

FIGURE 7
Solenoid Valve With External Variable Orifice

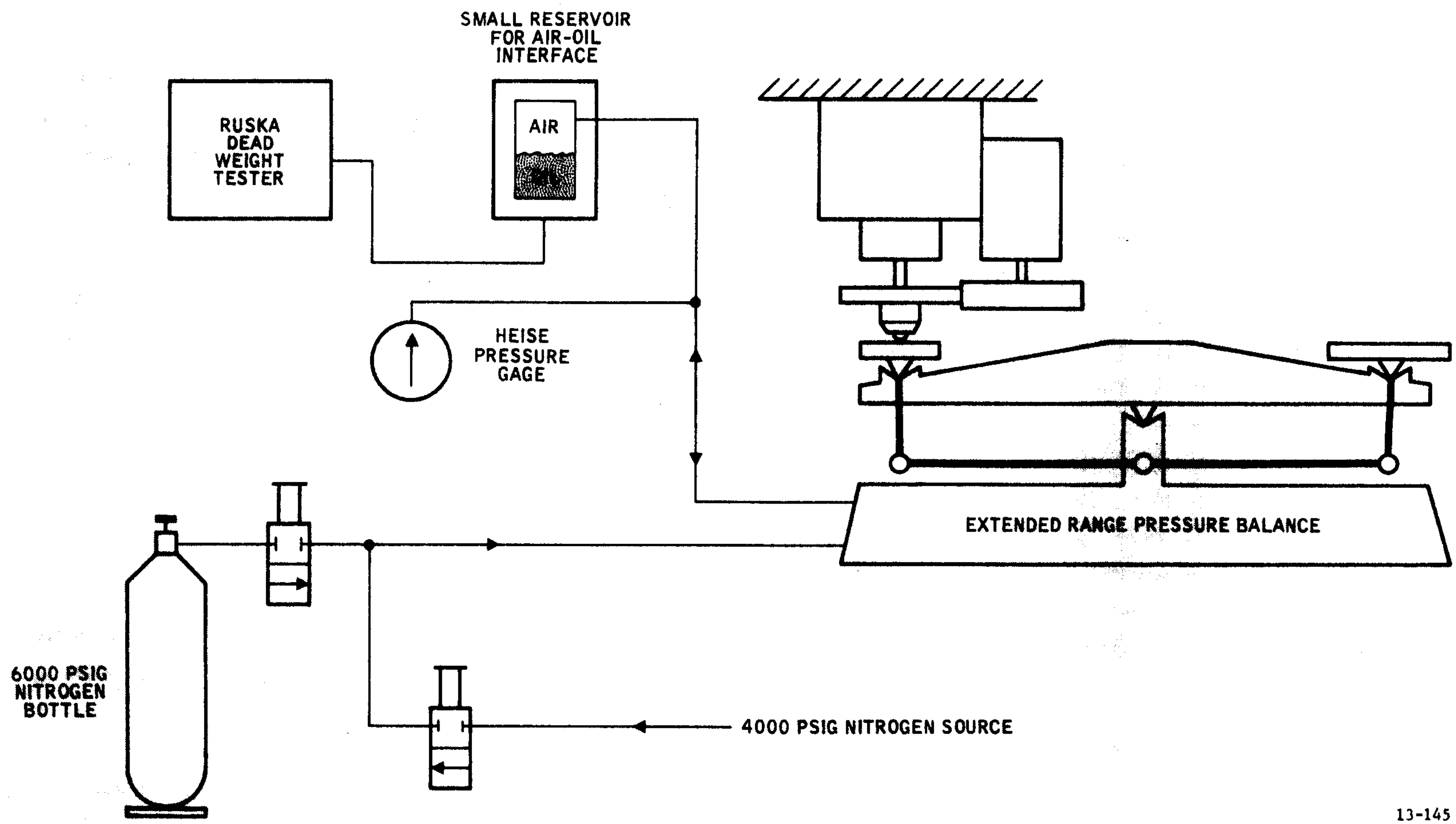

FIGURE 8
Schematic - Evaluation Test Setup

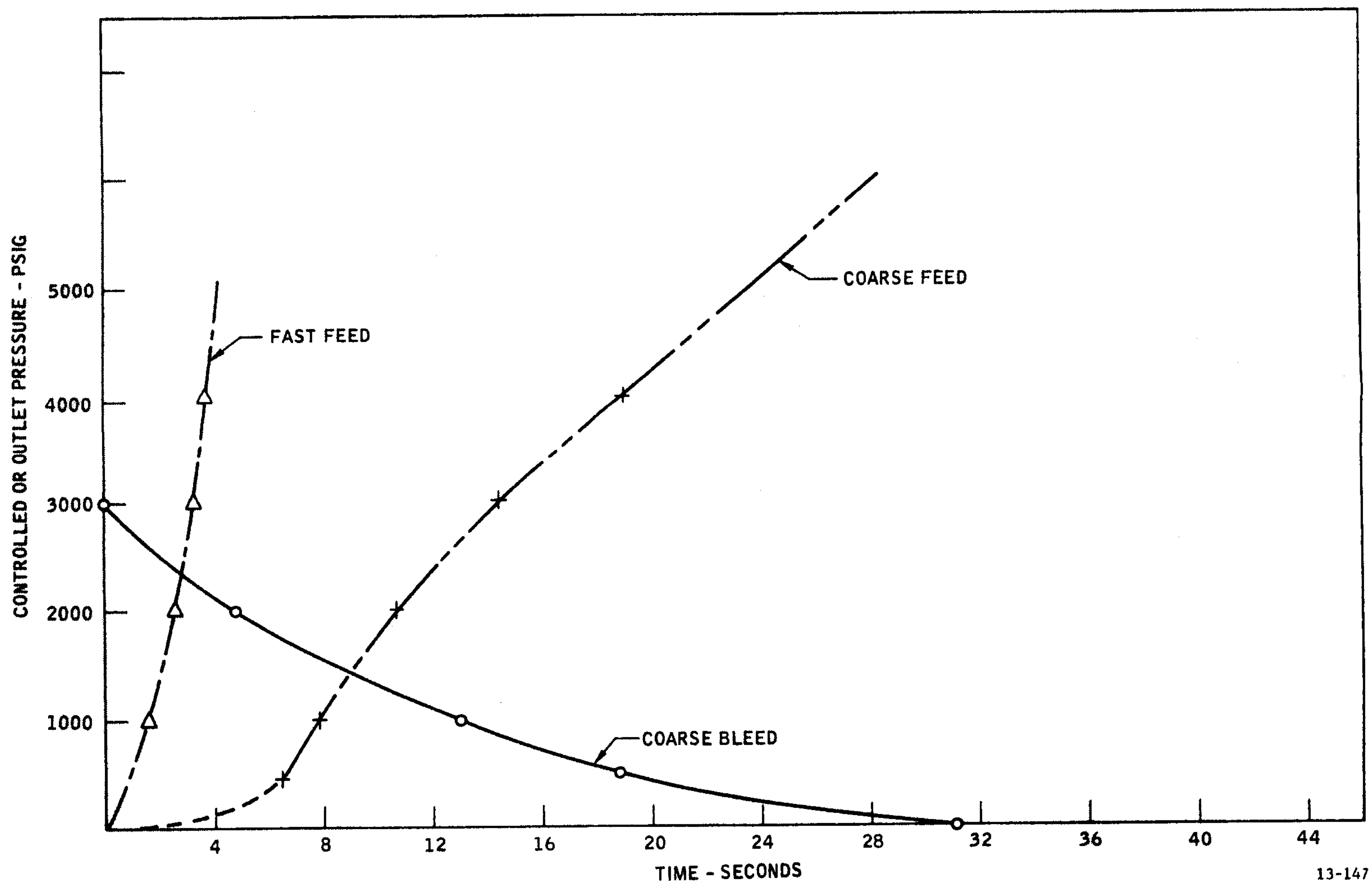

FIGURE 9
Minimum Volume Response Curves
For Extended Range Dead Weight Pressure Balance

1	2	3	4	5	6	7
Outlet Pressure (P_3) PSIG	Regulator Outlet Pressure (P_2) PSIG	Differential Pressure (P_2 - P_3) PSI	Pressure Ratio (P_2/P_3)	$(P_2/P_3)^{.283}$	$\sqrt{\text{Col.5(Col.5-1.0)}}$	Normalized Weight Flow #1-Min (Col.1-10^{-3}) x (Col.6)
169	319	150	1.89	1.1975	0.485	0.082
250	400	150	1.60	1.142	0.403	0.101
500	650	150	1.30	1.077	0.288	0.144
750	900	150	1.20	1.053	0.236	0.1775
1,000	1,150	150	1.15	1.0403	0.2045	0.2045
1,250	1,400	150	1.12	1.0326	0.1835	0.229
1,500	1,650	150	1.10	1.0273	0.1675	0.255
2,000	2,150	150	1.075	1.0206	0.1450	0.290
2,500	2,650	150	1.06	1.0162	0.1281	0.321
3,000	3,150	150	1.05	1.0139	0.1189	0.356
3,500	3,650	150	1.042	1.0117	0.1089	0.380
4,000	4,150	150	1.0375	1.0105	0.1030	0.411
4,500	4,650	150	1.033	1.0093	0.0969	0.436
5,000	5,150	150	1.03	1.0084	0.0920	0.460

TABLE 1
Tabulate Values
Empirical Weight-Flow vs Outlet Pressure

Pressure* PSIG	Fine Feed Solenoid Cycle/Second	Coarse Feed Solenoid Cycle/Second
500	Very Stable - no data recorded	Very Stable - no data recorded
1,000	2	-
2,000	1 1/2	-
3,000	2	0.7
4,000	2	0.1
5,000	4 to 5 actuations to 1 of feed solenoid. Cycling rate of about 1 CPS	-

*Outlet or Controlled Pressure.

TABLE 2
"Fine" Feed-Bleed Oscillatory Rates